PPSE-2-8

PPRP

FINAL REPORT

PREDICTION OF THE EFFECTS OF NUTRIENT LOADINGS FROM A POWER PLANT AT PERRYMAN ON THE WATER QUALITY OF THE BUSH RIVER ESTUARY

Prepared by

K.A. Rose
R.L. Dwyer
M.A. Turner

Martin Marietta Environmental Systems
9200 Rumsey Road
Columbia, MD 21045-1934

MARYLAND DEPARTMENT OF NATURAL RESOURCES
TIDEWATER ADMINISTRATION

POWER PLANT AND ENVIRONMENTAL REVIEW

October 1986

PREDICTION OF THE EFFECTS OF NUTRIENT LOADINGS FROM A POWER PLANT AT PERRYMAN ON THE WATER QUALITY OF THE BUSH RIVER ESTUARY

Prepared by

K.A. Rose
R.L. Dwyer
M.A. Turner

Martin Marietta Environmental Systems
9200 Rumsey Road
Columbia, MD 21045-1934

Prepared for

Department of Natural Resources
Power Plant Research Program
Tawes State Office Building
Annapolis, Maryland 21401

October 1986

FOREWORD

This report, "Prediction of the Effects of Nutrient Loadings from a Power Plant at Perryman on the Water Quality of the Bush River Estuary", was prepared by K. Rose, R. Dwyer, and M. Turner of Martin Marietta Environmental Systems at the request of T. Magette of the Power Plant Research Program (PPRP), Maryland Department of Natural Resources. This report documents work done under Tasks SA-1 through SA-5 of PPRP contract number P35-85-01 and Tasks PER-3 through PER-10 of contract number P35-85-01(86). This report is one of a series evaluating the suitability of the Perryman site for the location of a steam electric station.

Draft, March 1986
Revised, October 1986

ABSTRACT

A water quality model consisting of a one-dimensional Hydraulic Module coupled with a Water Quality Module was used to assess the effects of increased nutrient loadings from the proposed Perryman Power Plant on the dissolved oxygen and chlorophyll-a concentrations in the Bush River estuary. The Hydraulic Module represented the longitudinal water movement (and physical transport of associated constituents) among 12 spatial segments. The Water Quality Module represented the biological processes affecting nitrogen, phosphorus, chlorophyll-a, and dissolved oxygen in each segment (e.g., photosynthesis, nutrient uptake, decomposition). The Hydraulic Module was calibrated and validated using observed tide heights, current velocities, and salinity gradients. The Water Quality Module was calibrated to data from a 9-month survey, and validated using data from three 36-hour surveys and estimates of water column oxygen production and consumption rates.

Model analyses showed that the effects of increased nutrient loadings from a 4-unit, closed-cycle Perryman Plant using makeup water from the Baltimore Water Supply (Loch Raven Reservoir or Conowingo Pond) on dissolved oxygen and chlorophyll-a concentrations were small under present, worst case, and likely future water quality conditions in the Bush River. Model analyses also showed that the small effects predicted for nutrient loadings from a Perryman Plant were due to the small magnitude of the loadings relative to the volume of the receiving waters, rather than due to the model's inability to predict higher chlorophyll-a or lower dissolved oxygen concentrations. Under nutrient loadings greatly in excess of the expected loadings from a 4-unit, closed-cycle Perryman Plant, chlorophyll-a and dissolved oxygen concentrations substantially different from calibration concentrations were predicted by the model. Monte Carlo error analysis of parameter uncertainty enabled estimation of the variability of model predictions under different nutrient loading levels and allowed identification of the parameters for which more precise estimates would result in the greatest reduction in model prediction error.

TABLE OF CONTENTS

TABLE OF CONTENTS Continued

RP-490, RP-511, RP-567

LIST OF TABLES

LIST OF TABLES Continued

LIST OF TABLES Continued

LIST OF FIGURES

LIST OF FIGURES Continued

LIST OF FIGURES Continued

LIST OF FIGURES Continued

LIST OF FIGURES Continued

LIST OF FIGURES Continued

LIST OF FIGURES Continued

LIST OF FIGURES Continued

I. INTRODUCTION

A. BACKGROUND

The Baltimore Gas and Electric Company (BG&E) is planning to construct a fossil fuel-fired power plant on the Perryman site in Harford County, MD, adjacent to both the Bush River and the U.S. Army Aberdeen Proving Ground. This site has been owned by the utility for a number of years, and has been the subject of study by both utility and state contractors.

The proposed power plant at Perryman will be the latest in a series of environmental alterations that have influenced water quality in the Bush River over the years. Suspected causes of water quality degradation include: development of the U.S. Army's Aberdeen Proving Ground; increased runoff from cultivated adjacent land; sedimentation due to residential development; and discharge of treated sewage from the Sod Run Waste Water Treatment Plant (WWTP). Due to the number and variety of these perturbations, flexible modeling tools are needed to predict any incremental effects of power plant operations on water quality. PPRP therefore requested that Martin Marietta Environmental Systems evaluate existing water quality models that might be applicable to the Perryman site.

This evaluation:

- Defined the factors that should be incorporated into an assessment of potential impacts of a Perryman Plant on Bush River water quality

- Evaluated the usefulness and flexibility of existing modeling tools for making such an assessment

- Outlined modifications to those models that would enhance their utility.

Based on the evaluation of various water quality modeling packages, EPA's Dynamic Estuary Model (DEM) appeared to possess the major features needed for an assessment of the potential impacts of the Perryman Plant on water quality (e.g., nutrients, dissolved oxygen). The DEM package is built upon a one-dimensional Hydraulic Module that appeared capable of simulating the gross transport and dilution of discharge constituents. We also found that the module could accept boundary conditions that vary over time.

This capability is necessary because variations in both freshwater inflow and tidal amplitude are thought to cause variability in the circulation of the Bush River.

The initial study found that the DEM package has a Water Quality Module coupled to the Hydraulic Module that is capable of simulating the major processes thought to affect water quality in the Bush River:

- Phytoplankton growth as a function of nutrient and light availability

- Oxygen dynamics as controlled by phytoplankton metabolism, decomposition of organic matter, sediment oxygen demand, and air-water diffusion.

Interactions between nutrient loadings, phytoplankton biomass, and dissolved oxygen (DO) concentrations are of concern because:

- The Bush River is already enriched with nutrients from land runoff and the discharge of the Sod Run WWTP.

- Some intake-discharge configurations for the Perryman Plant could increase nutrient loadings, which could, in turn, cause increases in phytoplankton biomass and reductions in DO concentrations.

The water quality criteria in the Code of Maryland Regulations require that DO concentrations be at or above 5 mg/L at all times. While the State of Maryland has not established a criterion for chlorophyll-a concentrations in natural waters, "greenness," or chlorophyll-a concentration, is an accepted indicator of estuarine water quality (Jaworski 1981; McErlean and Reed 1981; Darnell and Soniat 1981). Generally, chlorophyll-a concentrations greater than 80-100 μg/L are thought to indicate enrichment or nuisance algal concentrations (Ketchum 1969; Jaworski et al. 1972). Recently, some states have begun to implement water quality criteria for chlorophyll-a concentrations in estuarine waters (e.g., State of North Carolina Administrative Code, Section 2B.0212(B)).

While the DEM package appeared capable of meeting most of the needs of the water quality assessment study, some possible deficiencies in the formulations of the Water Quality Module were identified. The necessary modifications were finalized during the process of calibrating and validating the Water Quality Module. (The final version of the Water Quality Module used is described in detail in Chapter III of this report.)

B. REPORT ORGANIZATION

Chapter II of this report describes the steps taken to calibrate the Hydraulic Module of DEM. Chapter II first presents the basic structure and capabilities of the Hydraulic Module, and the spatial segmentation chosen for the application of the model to the Bush River. The Hydraulic Module was first calibrated using data from hydrographic surveys conducted in 1972 and 1973. Because these data were not sufficient to validate the Module, it was necessary to collect additional tide data. The new tide data were analyzed and subsequently served as the basis for full calibration and validation of the Module. As further validation of the Module, water velocity data, which were collected along with the new tide data, were compared with internal currents simulated by the Module.

Chapter II also describes the steps used to identify and set up the physical data needed to simulate the hydrodynamics of the Bush River for the periods used in the calibration and validation of the Water Quality Module, as well as for the simulations of hypothetical scenarios involving Perryman Plant discharges. A major concern addressed in this Chapter is the estimation of surrogate tide data for the mouth of the Bush River, needed to drive the Hydraulic Module at its downstream boundary. Since tide heights at the river mouth were not measured for most of the time periods of interest, several methods of estimating the needed tide data were evaluated. These methods are described in detail in Appendix A.

Chapter III presents a detailed description of the formulations of the final version of the Water Quality Module of DEM used in this study. EPA's DEM software package contains a number of options for choosing different formulations to simulate different situations. However, this report documents only the model options actually used in this study.

Chapter IV describes the calibration of the Water Quality Module, as well as the validation permitted by the amount and quality of the available data. The chapter begins with a review of the available data, and the limitations the data place on the calibration/validation process. This is followed by a description of the estimation of data required as inputs for simulations with the Water Quality Module. Finally, the chapter describes the results of the calibration and validation (i.e., comparison of observed data with model predictions).

Chapter V describes the completion of the major objective of the study--the simulation of hypothetical scenarios for the effects of discharge of effluents from the Perryman Power Plant on Bush River water quality. Two major groups of scenarios were run:

- Simulations of the effects of the Perryman discharge on water quality under existing (1984) conditions

- Simulations of the effects of the Perryman discharge on the water quality under possible future conditions (increased Sod Run discharges and improved water quality due to the imposition of non-point source pollution controls).

Chapter VI describes an error analysis of the calibrated model. Using Monte Carlo simulation methods, the relative importance of parameters in controlling model behavior and the uncertainty in model predictions due to uncertainty in parameter values are assessed. Based on these results, parameters for which improved measurement would result in the greatest reduction in model prediction uncertainty are identified.

Finally, Chapter VII summarizes the modeling approach used in this study, and presents our conclusions on the likely effects of the Perryman Power Plant on the water quality of the Bush River.

II. APPLICATION OF THE HYDRAULIC MODULE OF DEM TO THE BUSH RIVER ESTUARY

A. INTRODUCTION

The Hydraulic Module of DEM provides a dynamic representation of estuarine transport--it can be used to estimate the one-dimensional, longitudinal circulation of an estuary from spatial differences in water elevations along the estuary. The model is formulated so that transport depends on the boundary conditions of tide height at the seaward boundary of the estuary, freshwater flow at the landward end of the estuary, and the geometry of the estuary. Local wind forcing and Coriolis effects are neglected. The Hydraulic Module solves the equations of motion and continuity so as to describe the propagation of the tidal wave up a shallow estuary. The equations are solved numerically using a finite difference scheme that necessarily incorporates a number of approximations. The estuary must be divided longitudinally into discrete segments, and continuous time must be divided into finite steps; these together form the computational network for the finite difference equations of the model.

B. HYDRAULIC MODULE THEORY

The Hydraulic Module of DEM represents the estuary as an interconnected series of "junctions" and "channels." Other applications of DEM refer to these as "nodes" and "links," respectively. A junction is a segment of estuary volume containing both water and associated masses of constituents. A channel connects two junctions and transports water and constituents between them. The network of junctions for a hypothetical estuary is shown in Fig. II-la, and the associated channel network is shown in Fig. II-lb. The junction and channel network overlap to form the model network (Fig. II-lc). Figure II-ld illustrates the notation used to set up the finite difference equations.

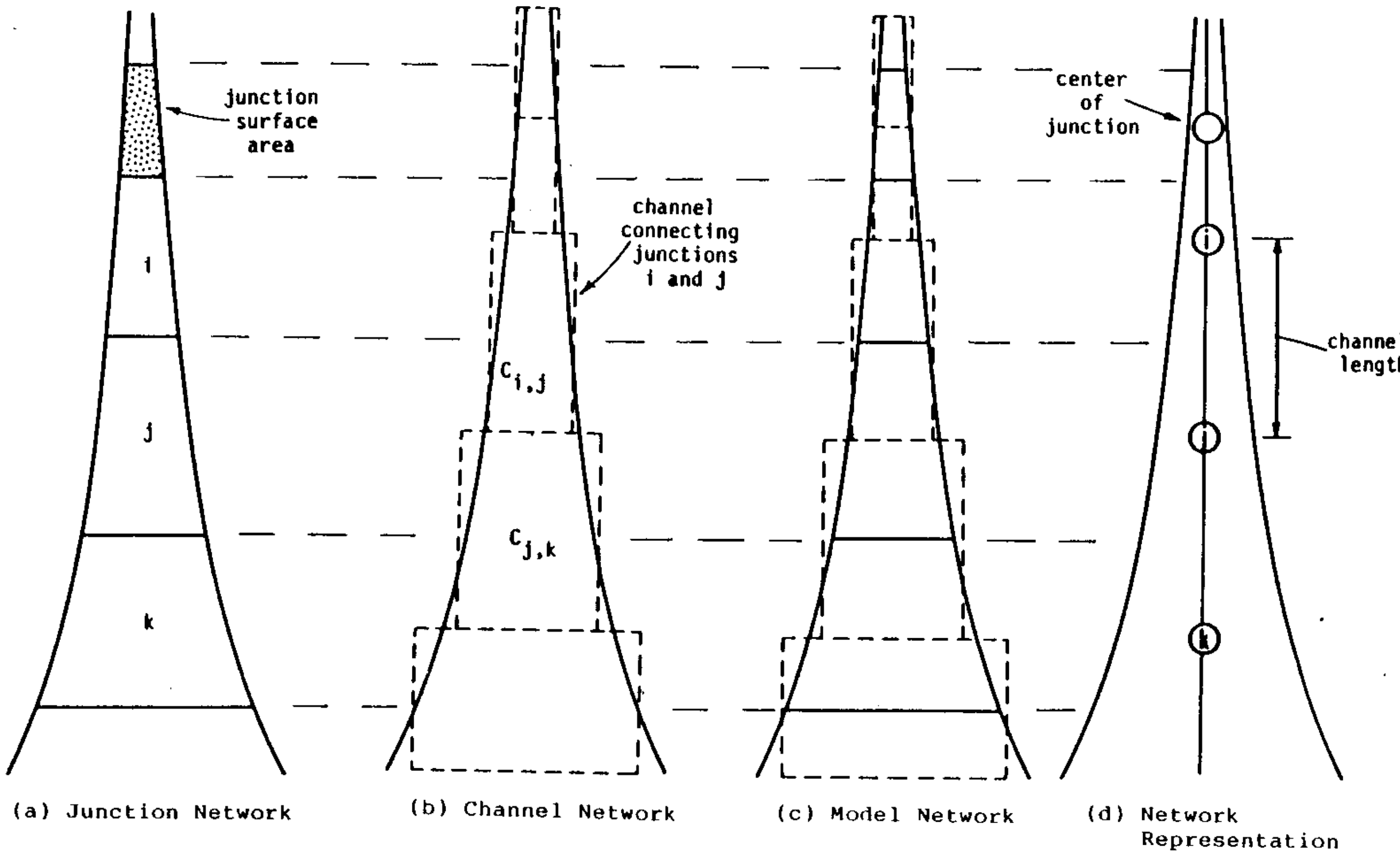

Figure II-1. Model representations of (a) junctions, (b) channels, (c) combined model network, and (d) symbolic representation of model network (after Roesch et al. 1979)

Channels have the following properties:

- Length: dimension along the direction of maximum water flow, equal to the distance between the two junctions it connects
- Width: average distance between estuary banks
- Cross-sectional area: the product of the channel's width and depth
- Bottom roughness: drag of the bottom on water flow (the Hydraulic Module is calibrated by adjustment of the Manning coefficients for bottom roughness)
- Hydraulic radius: for estuaries with width greater than 10 times channel depth, the hydraulic radius is assumed equal to the mean channel depth.

Junctions have the following properties:

- Surface area: the average of the surface areas of all channels that adjoin the junction
- Volume: the product of the junction surface area and the average depth (weighted by the cross-sectional areas of the adjoining channels)
- Hydraulic head: water surface elevation with respect to an arbitrary datum (usually mean sea level or mean low water).

The one-dimensional equation of motion is applied to the network of channels to estimate velocities and water fluxes. The equation of motion is:

$$\frac{\partial U}{\partial t} = -U \frac{\partial U}{\partial X} - k|U|U - g \frac{\partial H}{\partial X} \qquad \text{(II.1)}$$

where:

U = velocity along the major axis (ft/s)

t = time (s)

X = distance along the major axis (ft)

k = frictional resistance coefficient (ft^{-1})

g = acceleration of gravity (ft/s^2)

H = head (height of the water surface above an arbitrary datum, ft).

The four terms of Eq. II.1 are, respectively:

- The time rate of change of velocity
- The rate of change in momentum by mass transfer
- Resistance of bottom friction to flow (the absolute value causes resistance to oppose the direction of velocity)
- Gravitational acceleration due to head differences between junctions.

The frictional resistance coefficient, k, is:

$$k = \frac{g\ n^2}{2.208\ R^{4/3}} \qquad \text{(II.2)}$$

where:

R = hydraulic radius of the channel

n = Manning's coefficient for bottom drag.

The equation of continuity guarantees the conservation of mass:

$$\frac{\partial H}{\partial t} = - \frac{1}{b} \cdot \frac{\partial Q}{\partial X} \qquad \text{(II.3)}$$

where:

H = head (ft)

b = mean channel width (ft)

Q = flow (ft^3/s).

Equation II.3 relates the time rate of change of the water surface elevation in a junction to the change in storage (in flow) along the channel length (per unit width).

Thus, in the model network, the properties of flow and velocity are associated with the channels (Eq. II.1) while changes in water surface elevation and volume are properties of the junctions (Eq. II.3).

To permit their numerical solution, the equations of motion and continuity must be converted into finite-difference form:

$$\frac{\Delta U_k}{\Delta t} = -U_k \frac{\Delta U_k}{X_{I_k}} - k|U_k|U_k - g\frac{\Delta H}{X_k} \qquad \text{(II.4)}$$

$$\frac{\Delta H_j}{\Delta t} = \frac{\Sigma Q_j}{A_j} \qquad \text{(II.5)}$$

where:

A_j = surface area of the junction N (ft^2)

ΣQ_j = sum of all inflows (i.e., from channels, waste inflows, and tributaries).

To solve these finite-difference equations, the Hydraulic Module uses a Runge-Kutta numerical integration scheme (Mejer 1983). Complete descriptions of the structure of the Hydraulic Module of DEM, and methods for its application, were presented by Feigner and Harris (1970) and Roesch et al. (1979).

C. CALIBRATION AND VALIDATION OF THE HYDRAULIC MODULE OF DEM FOR THE BUSH RIVER ESTUARY

The appropriateness of using a one-dimensional model to represent the circulation of the Bush River estuary was confirmed by a qualitative examination of available data. Data sources included the 1971-1972 hydrographic surveys of the estuary (Hydrocon, Inc. 1972; CBI/APL unpublished), water quality surveys conducted by DNR in 1977 (CH2M Hill 1983), water quality surveys conducted in 1981 and 1982 by CH2M Hill (1983), and productivity surveys conducted in 1984 (Boynton et al. 1985). Only the 1972 data showed any indication of vertical density stratification, and this was restricted to stations near the mouth on a few of the surveys. No data indicate the existence of any lateral variations in density or circulation. Thus, the use of a one-dimensional model to represent the circulation of the estuary appears valid.

Selection of the time interval, Δt, and the size of channels, ΔX, for the model network are intimately related, as determined by the Courant numerical stability criterion:

$$\Delta t < \frac{\Delta X}{(\sqrt{gR} + U)}. \qquad \text{(II.6)}$$

Compliance with the Courant stability criterion assures that the time step is short enough, or the channel is long enough, so that the water velocity (U) plus the speed of the shallow-water gravity wave ($\sqrt{gR}$) cannot move a parcel of water completely through and out of the channel within the time step. Selection of a time step and spatial segmentation scheme thus becomes a compromise between the competing goals of fine spatial resolution and economical computations (i.e., long time steps).

A version of DEM was previously applied to the Bush River estuary as part of a waste load allocation study for a proposed expansion of the Sod Run WWTP (CH2M Hill 1983). That study used 12 junctions to represent the Bush River and its three headwater branches: Winters Run, Bynum Run, and Gray's Run (Fig. II-2). Dimensions of the channels and junctions of this model network are listed in Tables II-1 and II-2. Using Eq. II-6 and the data in Tables II-1 and II-2, the maximum time step allowable for CH2M Hill's model network is ~ 400 s. Since the added computational costs of reducing the time step to allow more spatial resolution in the network were considered prohibitive, we decided to use CH2M Hill's model network.

Data Sources For Calibration and Validation of the Hydraulics Module

In 1972, two dye dilution experiments and several series of hydrographic measurements (temperature, salinity, suspended sediment concentration) were carried out in the Bush River by the Chesapeake Bay Institute (CBI) and Applied Physics Laboratory (APL) (both part of Johns Hopkins University) and by Hydrocon, Inc. (1972, 1973). Some continuous tide data were also collected during these studies.

The availability of the tide data and data for freshwater inflow from the streams feeding the head of the estuary indicated that the 1972 data might be sufficient to calibrate and validate the Hydraulic Module. In addition, extensive salinity data collected in 1972 could later be used to calibrate the dispersion coefficients of the Water Quality Module.

Accordingly, we attempted to use the 1972 data to calibrate and validate the Hydraulic Module. The tide data were available for the periods 18 April to 2 May, 28 September to 4 October, and 1-21 November 1972. The tide gauge was located at Otter Point Landing, at the head of the estuary (Fig. II-2). However, the model required, as its seaward boundary condition, tide data from the estuary mouth. Thus, the tide data from Otter Point Landing were not adequate for specification of the seaward boundary condition of the model. Because no other tide measurements near the mouth of the estuary were available, a field collection program was designed and implemented in September and

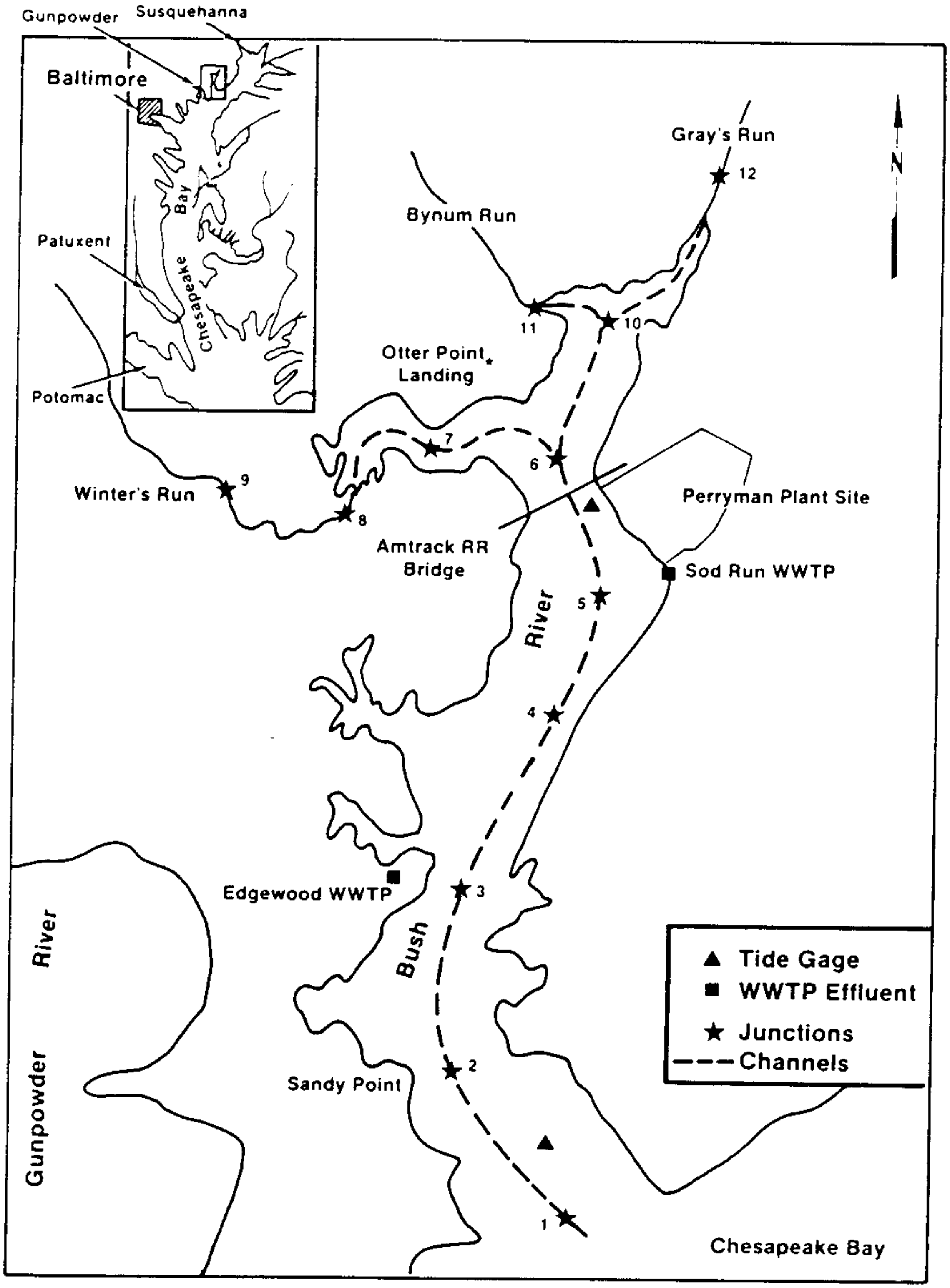

Figure II-2. Network of junctions for Bush River application of DEM. Also shown are locations of Sod Run WWTP, the Perryman River plant site, and the locations of hydrographic instrument arrays (tide gauges and a current meter).

Table II-1. Dimensions of channels of Bush River model network

Summary of Channel Data

Channel	Length (ft)	Width (ft)	Depth (ft)	C.S. Area (ft^2)	Junctions at Ends of Channel
1	9800	8000	7.0	55920	1, 2
2	9400	7500	6.3	47175	2, 3
3	9600	7000	5.6	38850	3, 4
4	7000	5000	5.6	28000	4, 5
5	7400	5500	5.7	31075	5, 6
6	6200	4000	4.3	17160	6, 7
7	8800	2200	2.9	6468	7, 8
8	8000	1100	2.7	2926	8, 9
9	7200	4000	4.4	17680	6, 10
10	5000	600	3.0	1824	10, 11
11	9000	1100	3.6	3916	10, 12

Table II-2. Dimensions of junctions of Bush River model network

Summary of Junction Data

Junction	Surface Area (10^4 ft^2)	Channels Entering Junction
1	3540	1
2	6472	1, 2
3	6440	2, 3
4	5412	3, 4
5	3904	4, 5
6	3140	5, 6, 9
7	1606	6, 7
8	540	7, 8
9	32	8
10	2430	9, 10, 11
11	36	10
12	178	11

October 1984 to collect data sufficient for the calibration and validation of the Hydraulic Module. This program is described in the next section.

Methods of 1984 Hydrographic Survey of the Bush River

The data required to calibrate and validate the model are:

- Continuous tidal elevation records taken near the mouth of the estuary, preferably covering at least half of the monthly neap-spring tidal cycle (these data are needed to specify the seaward boundary condition for the model)
- Continuous tidal elevation records from at least one location within the estuary, taken simultaneously with the tide data (tide data measured within the estuary are needed to validate that the water surface elevations at internal junctions simulated by the model reproduce measured tides)
- Continuous current velocity data collected at the location of the internal tide measurements in the estuary for the same period as the tide data (the continuous current data provide another means of validating the circulation simulated by the model. Correspondence between simulated and observed current velocities verifies that the model can reproduce water transport patterns within the estuary and correct simulation of the transport in the estuary is needed for accurate estimation of the transport of water constituents by the Water Quality Module).

Based on these criteria, two recording water depth gauges and a recording current meter were deployed between 23 September and 22 October 1984. To collect water surface elevation data at the estuary mouth, a submersible recording pressure instrument was secured to a bottom mooring and deployed in mid-channel (~ 8.5 ft depth) off Sandy Point (Fig. II-2). The instrument was a Sea Data Corp. CTDR (Conductivity, Temperature, Depth Recorder) set to record a moving average of pressure (to damp out the influence of surface waves) every 30 min. Upstream, a second instrument, a Sea Data TDR (Temperature and Depth Recorder), was set to record at 30 min intervals and deployed on the bottom near mid-channel in 6.5 ft of water about 250 yd downstream of the Amtrak railroad bridge (Fig. II-2). This location was chosen because of its proximity to BG&E's Perryman site (Fig. II-2). At the Railroad Bridge station, an Aanderaa RCM-4 current and conductivity meter, set at a 10 min recording interval, was deployed 3 ft from the bottom on the same mooring as the submersible depth gauge.

All instruments were recovered and serviced on 11 October 1984, 17 days after initial deployment. The self-checking routines of the microprocessors of the Sea Data TDRs were executed, batteries were checked, and cassette tapes were replaced. The Aanderaa current meter was checked for several recording cycles to verify correct operation. Both instrument moorings were redeployed at their respective stations.

Both instrument moorings were recovered on 22 October 1984. The TDR gauge and the Aanderaa current meter at the Railroad Bridge station were recovered intact. However, the CTDR at the Sandy Point station was flooded with seawater, which destroyed both the electronics package of the instrument and the data cassette. The damage to this instrument, which was apparently the result of vandalism, resulted in the loss of all data from the Sandy Point station after 11 October.

All intact data tapes were sent to the respective manufacturers for reading, conversion of data to standard units, and transfer to 9-track tape readable on the Martin Marietta Environmental Systems VAX computer.

Description of Tide Data

Tide data for the Sandy Point (mouth of Bush River) and Railroad Bridge (Perryman Plant site) stations are shown in Fig. II-3. The most pronounced characteristics are the semidiurnal tides and the slow changes in sea level. (Sea level periods are much longer than those of the semidiurnal tide.) The long-period sea level changes have been attributed to meteorological influences (see Appendix A). The magnitude of the contribution of the long-period components to the total tide record can be seen more readily after the raw data have been filtered to remove semidiurnal and higher frequency components. A linear filter was applied to the raw data (Bloomfield 1976). This filter, which was previously used to estimate nontidal currents in the Patuxent River (Polgar et al. 1980), used 151 hourly weights to calculate a weighted moving average.

The results obtained by filtering the Sandy Point data are shown in Fig. II-4. The top trace shows the raw data for Sandy Point (broken line) and the filtered data (solid line). The filter deletes 151/2, or 75, points from either end of the data set. The bottom trace shows the filtered complement data (raw data minus filtered data; dotted line). The long-period data appear to contribute up to 50% of the total amplitude of the tide data. The relationship of this long-period tidal component to meteorological forcing is discussed in Appendix A.

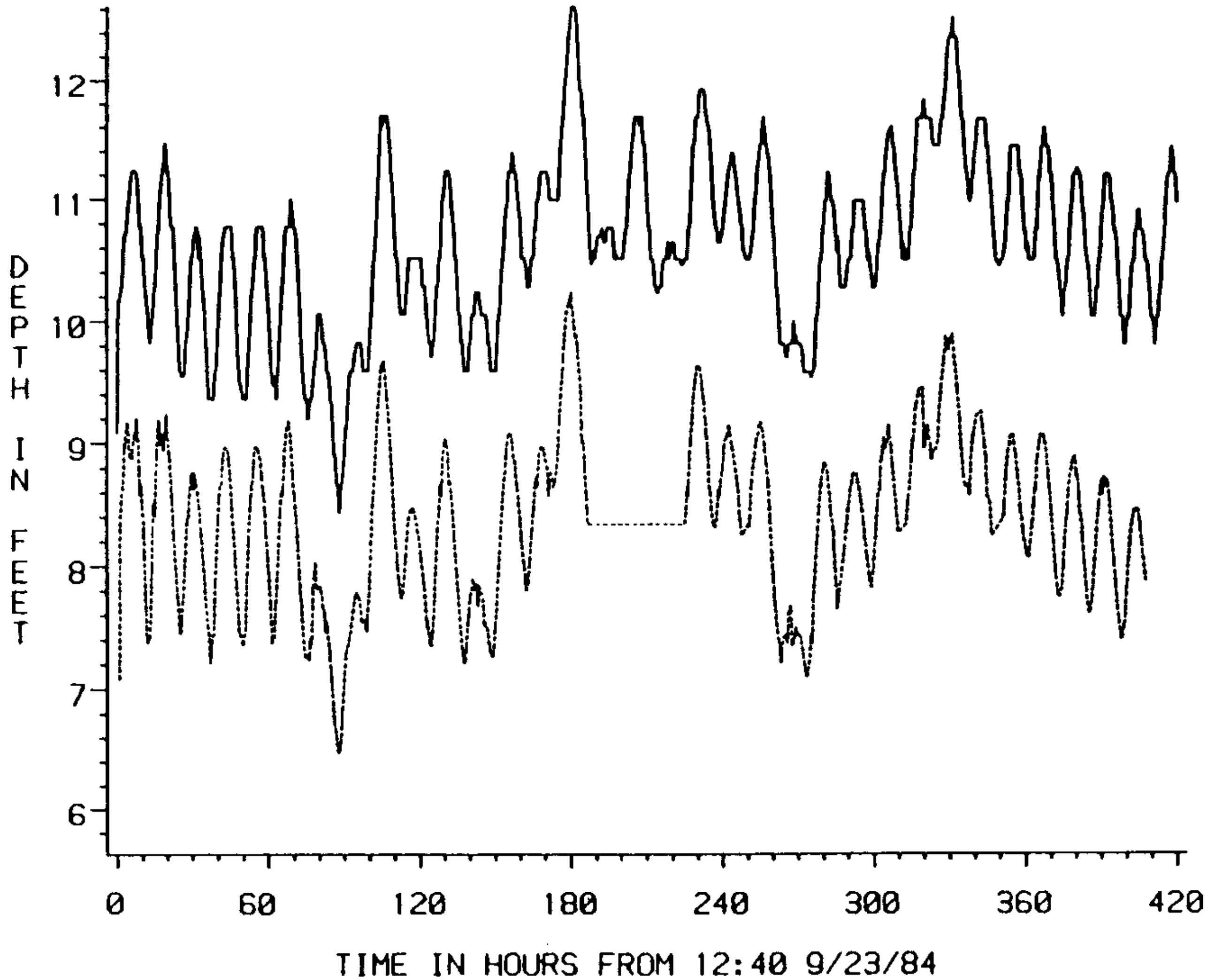

Figure II-3. Tide data collected at Sandy Point (solid line) and the Railroad Bridge (dotted line) between 23 September and 10 October 1984. Erroneous data points have been deleted from the Railroad Bridge plot.

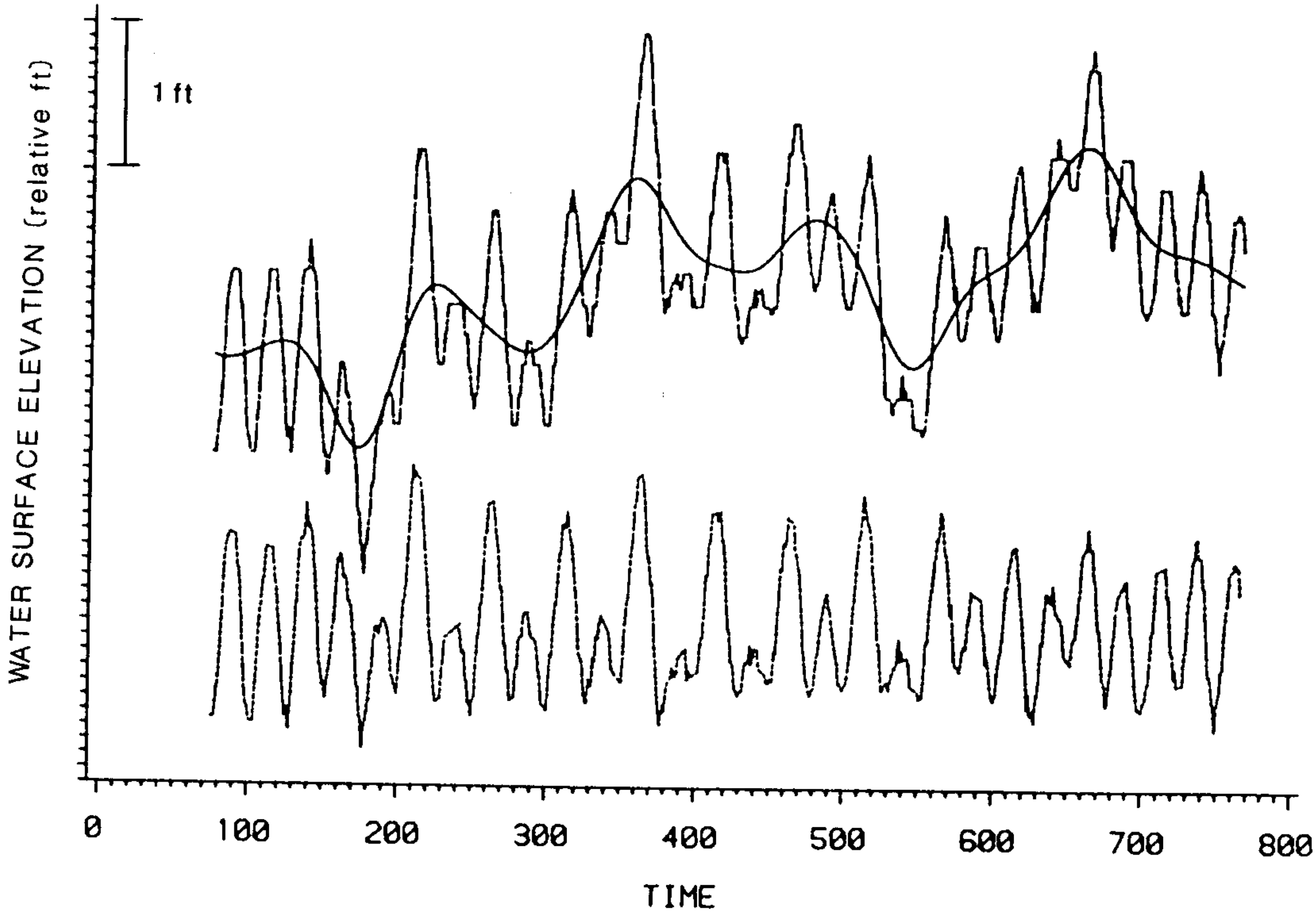

Figure II-4. Raw Sandy Point tide data (broken line), Sandy Point tide data smoothed using a low-pass filter (solid line), and filtered-complement data (dotted line). Time is number of 30-min intervals since deployment. See text for details.

Close examination of the Railroad Bridge tide data revealed a problem during the recording cycle of the TDR gauge. A self-checking routine noted numerous parity errors during the recording process, indicating that some of the data may have been erroneous. Examination of the data showed that there were extra periodicities at frequencies higher than those of the semidiurnal tide, and that some tide data showed values much lower than had been observed in the Bush River. Both of these problems are illustrated in Fig. II-5, which shows the first 2-1/2 days of the Railroad Bridge tide data (dotted line). The data were corrected by manually deleting obviously erroneous points and interpolating over the gaps (solid line).

The depths measured by the tide gauges were never referenced to a known vertical datum, thus Fig. II-3 provides only relative measures of water depth. However, the Hydraulic Module of DEM requires that all water surface elevations (heads) and hydraulic radii (depths) of junctions be related to a uniform datum. Mean Low Water is commonly used as a datum for hydrographic and cartographic purposes. Accordingly, the tide records from both stations were adjusted so that Mean Low Water corresponded to a head value of zero. Specifically, for each tide data set, the minimum water levels of each tidal cycle were identified, and the mean of these minima was calculated. This mean value was then subtracted from each of the observations of the data set to adjust the Mean Low Water value to zero. This process was used to adjust the heads at both Sandy Point and the Railroad Bridge to the same datum so that the model, when driven by boundary condition data from Sandy Point, would simulate accurate tides at an internal station--the Railroad Bridge. Failure to adjust the tide records to a common datum would have prevented any comparison of simulated tides at the Railroad Bridge to measured data.

Calibration of the Hydraulic Module

The first 3 days of the 17 days of tide data were used to calibrate the model. (The remaining 14 days of data were held in reserve for validation.) Freshwater inflow data were taken from CH2M Hill (1983). Their data were for average summer flow conditions at a USGS gauge on Winter's Run, one of the three streams feeding the head of the estuary. The flows for the three streams were derived from the ratio of each tributary's watershed area to that of Winter's Run above the gauge, multiplied by the flow value at the gauge. Freshwater inflow from the Sod Run WWTP was set at 10 cfs, or 6.5 million gallons per day (mgd), a value representative of Fall 1984. Values for all freshwater inflows are listed in Table II-3.

The Hydraulic Module was calibrated by trial-and-error adjustment of the Manning bottom friction coefficients. The

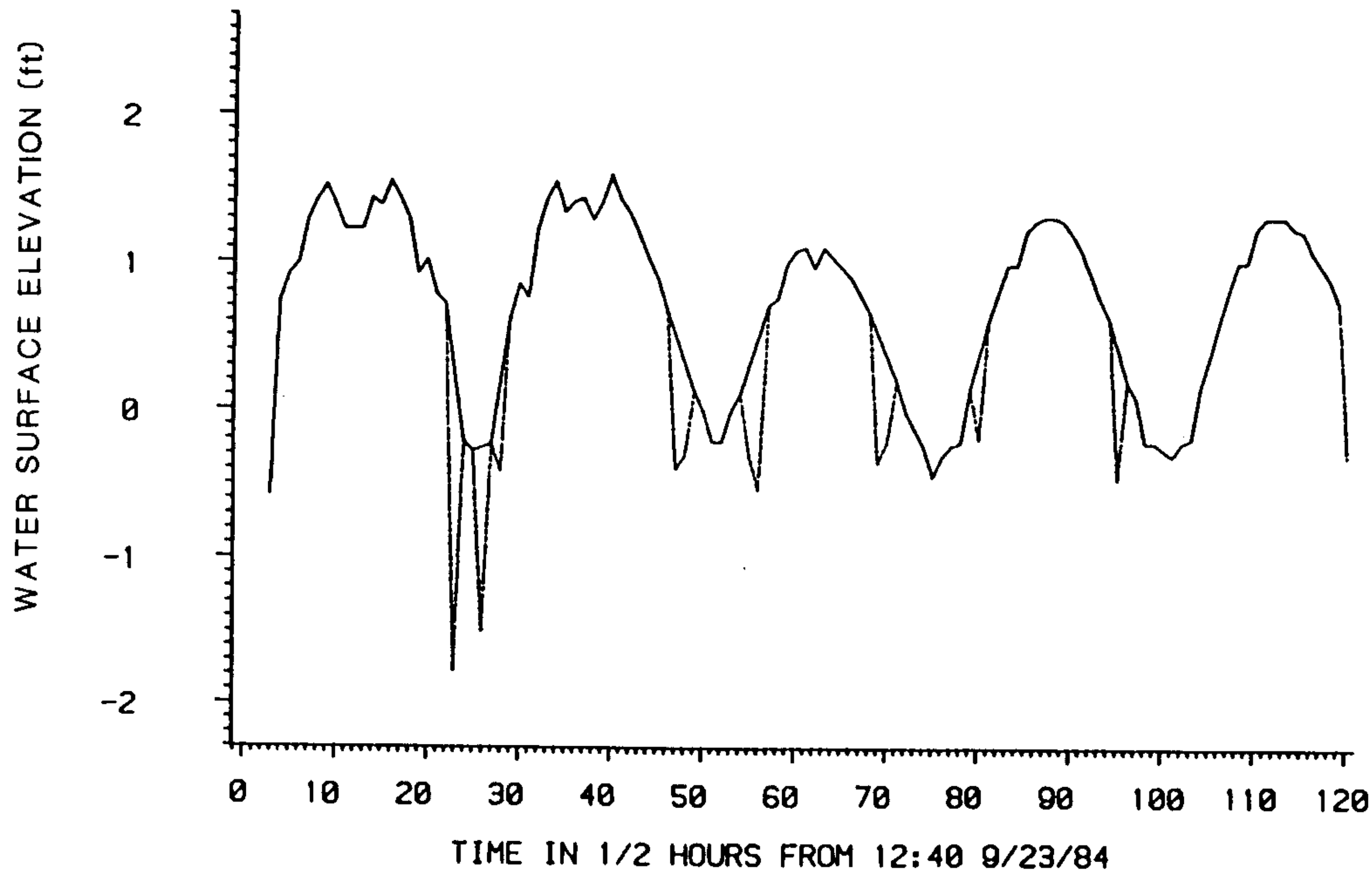

Figure II-5. Segment of Railroad Bridge data before deletion of erroneous data points (dotted line) and the same segment after deletion of erroneous data (solid line)

Table II-3. Constant flow inputs to junctions of Bush River model network

Junction	Flow (cfs)
12	19.6
11	44.1
9	73.5
5	10.1
3	1.9

best fit is shown in the first six tidal cycles (~ 150 time intervals) of Fig. II-6. The best fit values for the Manning coefficients are listed in Table II-4.

Validation of the Hydraulic Module

The remaining 14 days of data shown in Fig. II-6 verify that the model reproduced variations of water surface elevations (heads) within the estuary. Maximum deviations between simulated and observed tide heights during the validation period (time intervals 150-830) were at most 0.2 ft.

A second data set used to validate the model was the mid-depth (~ 3 ft) current data collected at the Railroad Bridge station. These data were taken at the same location as data collected by the TDR gauge. A comparison of these current measurements with currents predicted by the Hydraulic Module provides further validation of the fit of the model, since the model is driven at the downstream boundary by tide heights, not currents.

To permit the comparison, the raw current data were first partitioned into a component along the 160°-340° axis (the major axis of the river at the Railroad Bridge, and the most prevalent current direction found in the data). The observed component of current velocity (dotted line) and the velocities predicted for Channel 5 by the Hydraulic Module (solid line) are shown in Figs. II-7 and II-8. The first time period (Fig. II-7) corresponds to that used to calibrate the model. The second time period (Fig. II-8) is 8-10 days into the time period used to validate the model. In general, both records show that the model reproduces both the magnitude and phase of the semidiurnal component of velocity from current measurements at a single location. However, the model is unable to reproduce some of the higher-frequency components of current velocities. These components are not likely to be important in the gross circulation of the estuary, which is needed for the water quality modeling.

D. ESTIMATION OF DISPERSION COEFFICIENTS

One final preparatory step is needed before the Hydraulic Module can be linked to the Water Quality Module. The model's longitudinal dispersion coefficients must be calibrated so that conservative substances are correctly mixed among junctions. The significance of this dispersion and the calibration procedure are now described.

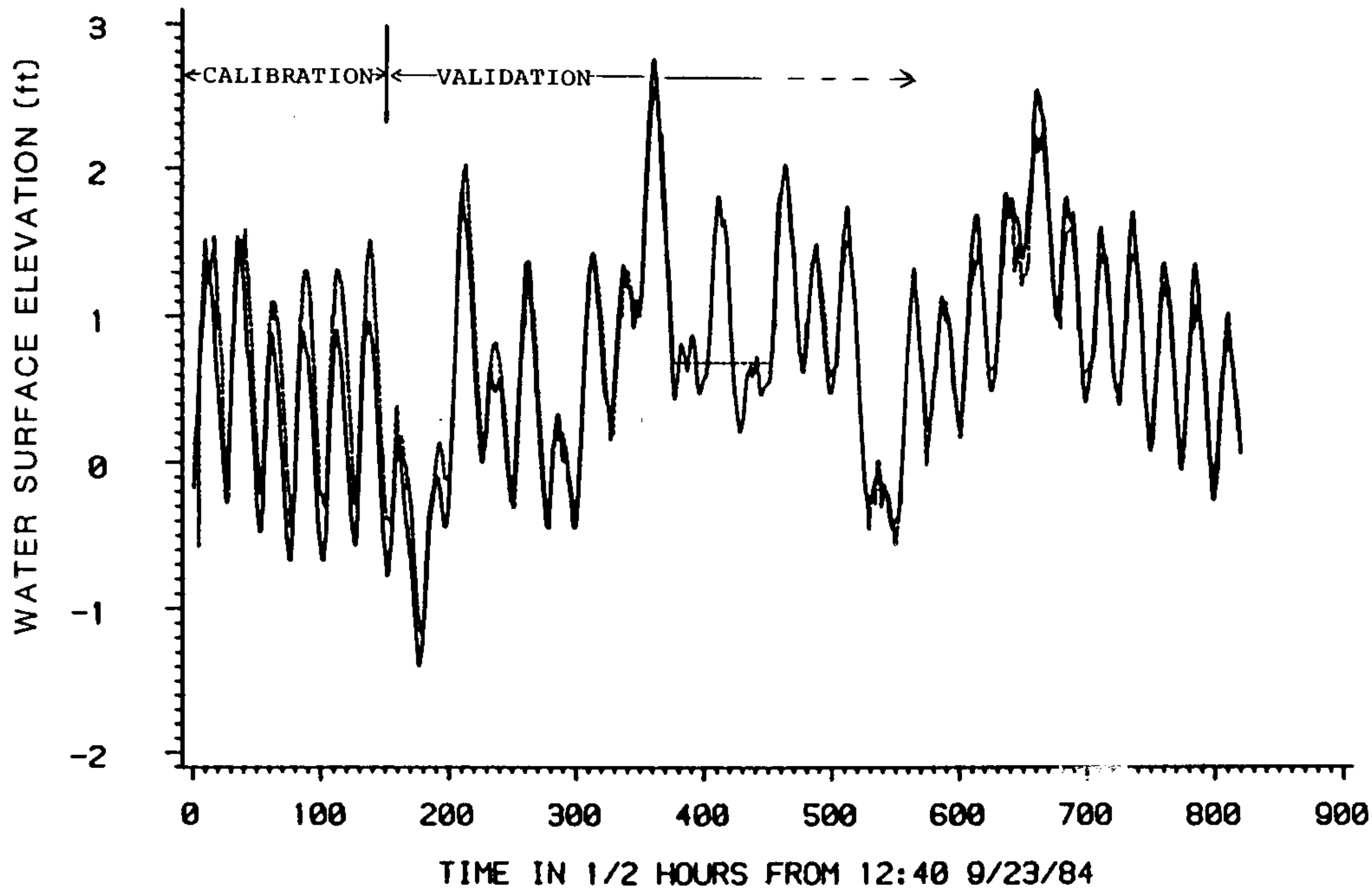

Figure II-6. Calibration and validation of the Hydraulic Module. Predicted water surface elevation in Junction 5 (solid line) vs. observed water surface elevation at Railroad Bridge station (dotted line). Segments used for calibration vs. validation are noted.

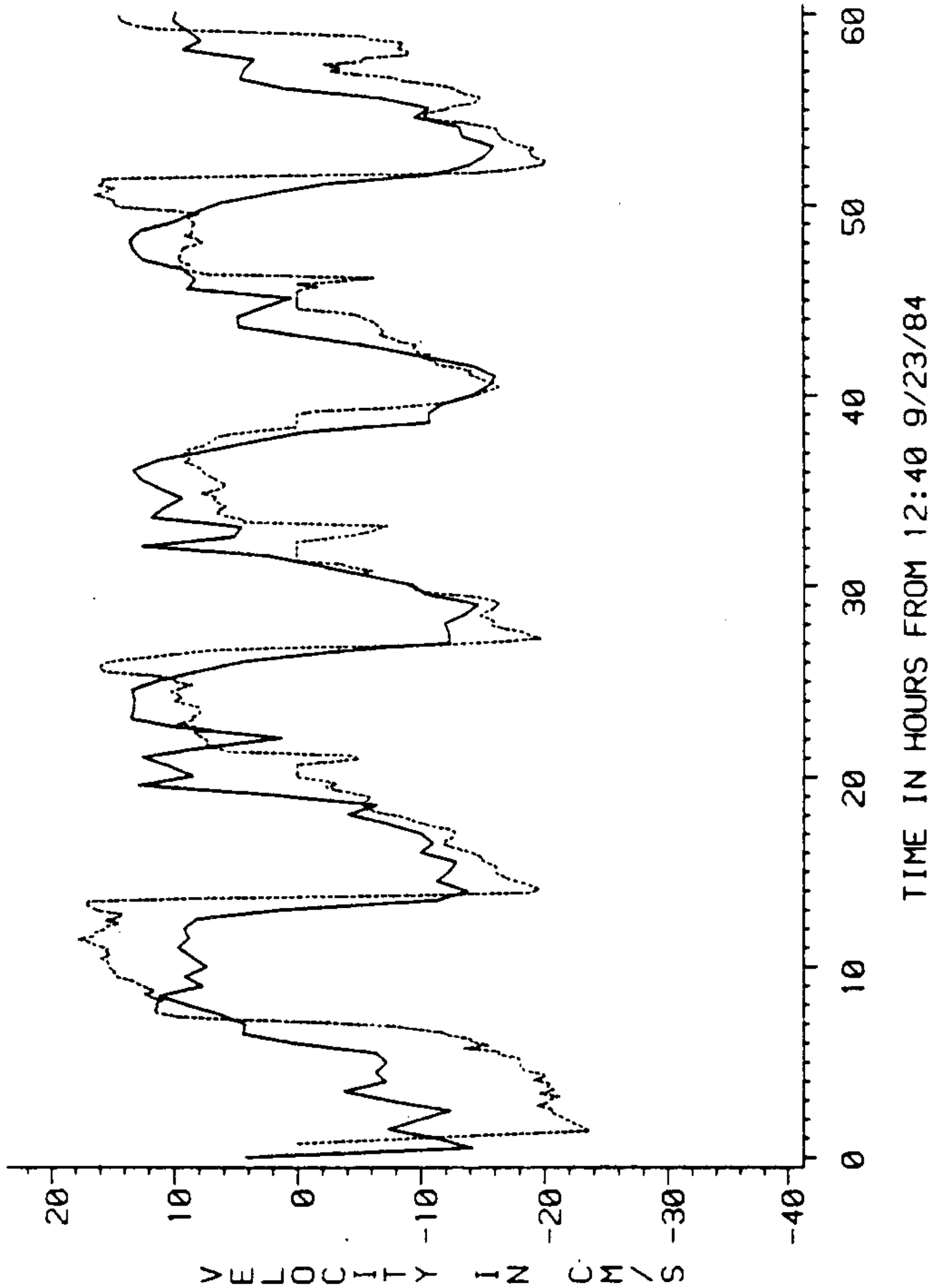

Figure II-7. Predicted velocity for channel joining Junctions 5 and 6 (solid line) vs. observed longitudinal velocity at Railroad Bridge station (dotted line)--calibration interval

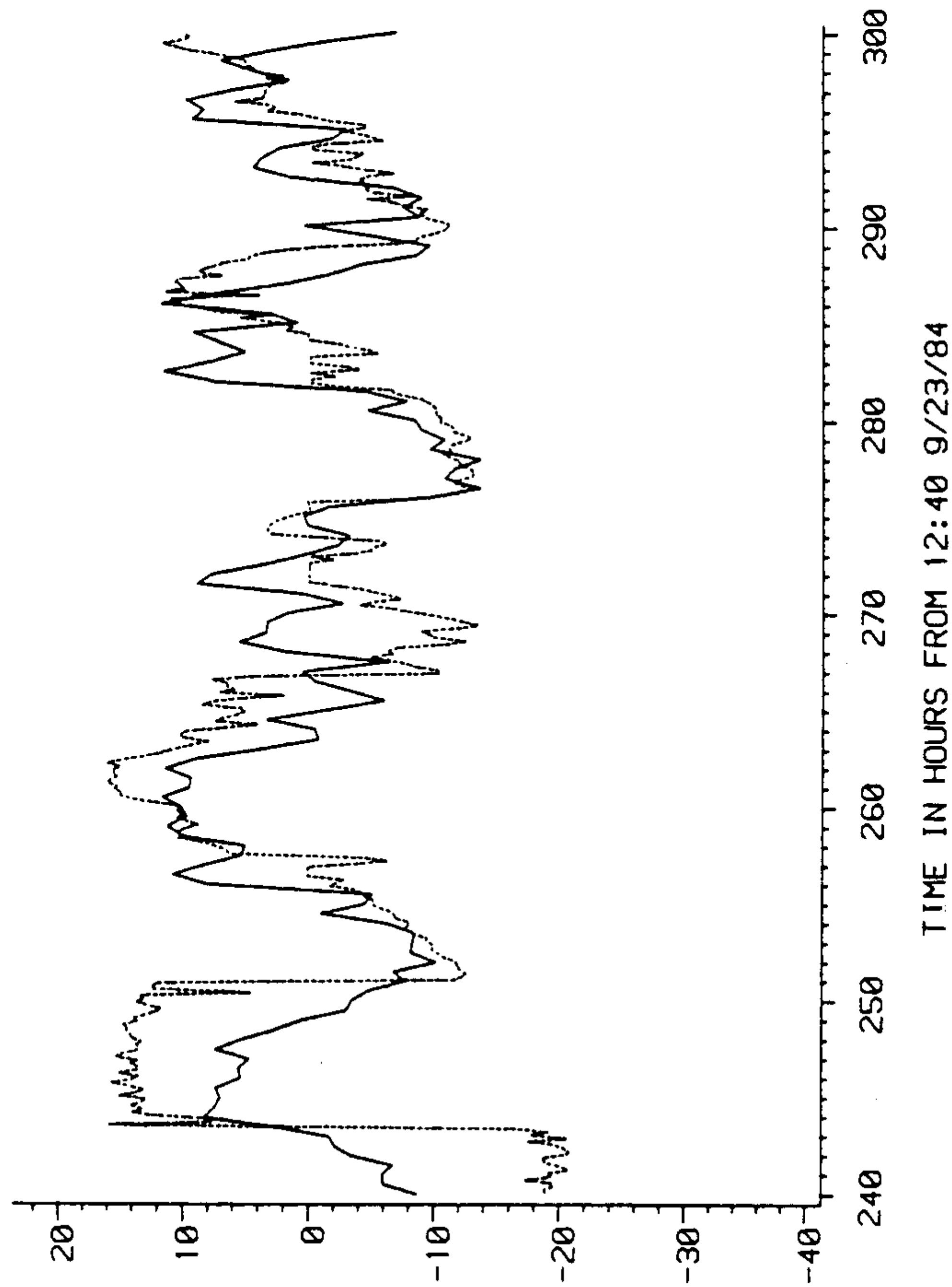

Figure II-8. Predicted velocity for channel joining Junctions 5 and 6 (solid line) vs. observed longitudinal velocity at Railroad Bridge station (dotted line)--segment of validation interval

Table II-4. Best-fit values for Manning coefficients of Hydraulic Module of DEM from 23-26 September 1984 calibration

Channel	Manning Coefficient
1	0.040
2	0.040
3	0.040
4	0.045
5	0.050
6	0.070
7	0.070
8	0.070
9	0.045
10	0.045
11	0.045

The Hydraulic Module represents transport between junctions as constant values over the cross-section of the estuary. However, real currents are not homogeneous across the estuary or with depth, and parcels of water or constitutents are subject to relative displacement due to these velocity differences. This is longitudinal dispersion. The model does not explicitly represent the velocity variations that control longitudinal dispersion (although coincidentally the model does produce some uncontrollable dispersion due to the approximations needed to solve the equations numerically).

Longitudinal dispersion is controlled in the model indirectly by the following equation (see Chapter III, Eq. III.6):

$$DIFFC_{kt} = KDIFFC \cdot |U_{kt}| \cdot R_{kt}$$

where:

KDIFFC = calibration parameter for all channels (unitless)

U_{kt} = water velocity in channel k at time t (ft/s)

R_{kt} = hydraulic radius of channel k at time t (assumed equal to the channel depth) (ft).

This computed value for $DIFFC_{kt}$ is then used in the calculation of the dispersion of all constituents (Chapter III, Eq. III.5).

An initial calibration of dispersion utilized the salinity data from 30 September to 4 October from the 1972 CBI/APL surveys. Initial salinity data were the 30 September values; boundary condition values for salinity were the Bay concentrations off the mouth of the Bush River for 1-4 October.

Values of 2.5, 25, 250, 500, and 5,000 were used for KDIFFC in calibration simulations. A value of 250 produced the best fits when predicted vs. observed salinities were plotted for Junctions 1 to 7 along the main stem of the river. Specifically, daily average predicted salinity was plotted with volume-averaged observed salinity for each of the four days (Figs. II-9 to II-12). The dispersion coefficients ($DIFFC_{kt}$) ranged from 45-90 ft^2/s; these values are reasonable and are similar to dispersion values estimated for the nontidal reach of the Susquehanna River below Conowingo Dam (Dwyer and Turner 1982).

After this calibration, the Hydraulic Module is now ready for linking to the Water Quality Module (next chapter).

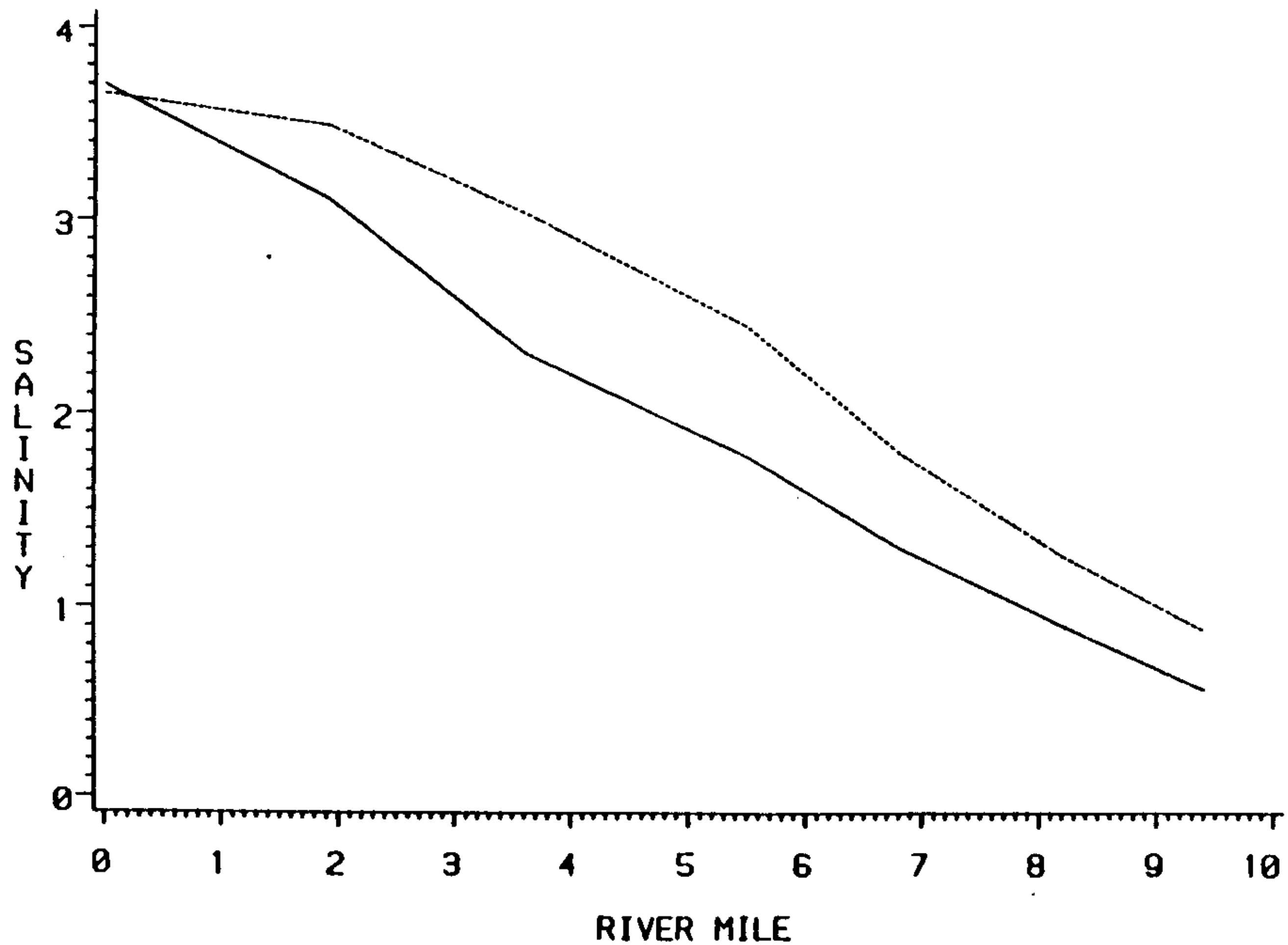

Figure II-9. Calibration of model dispersion. Observed salinities along Bush River (solid) vs. tidally-averaged salinities predicted by the model (dotted) by river mile for 1 October 1972

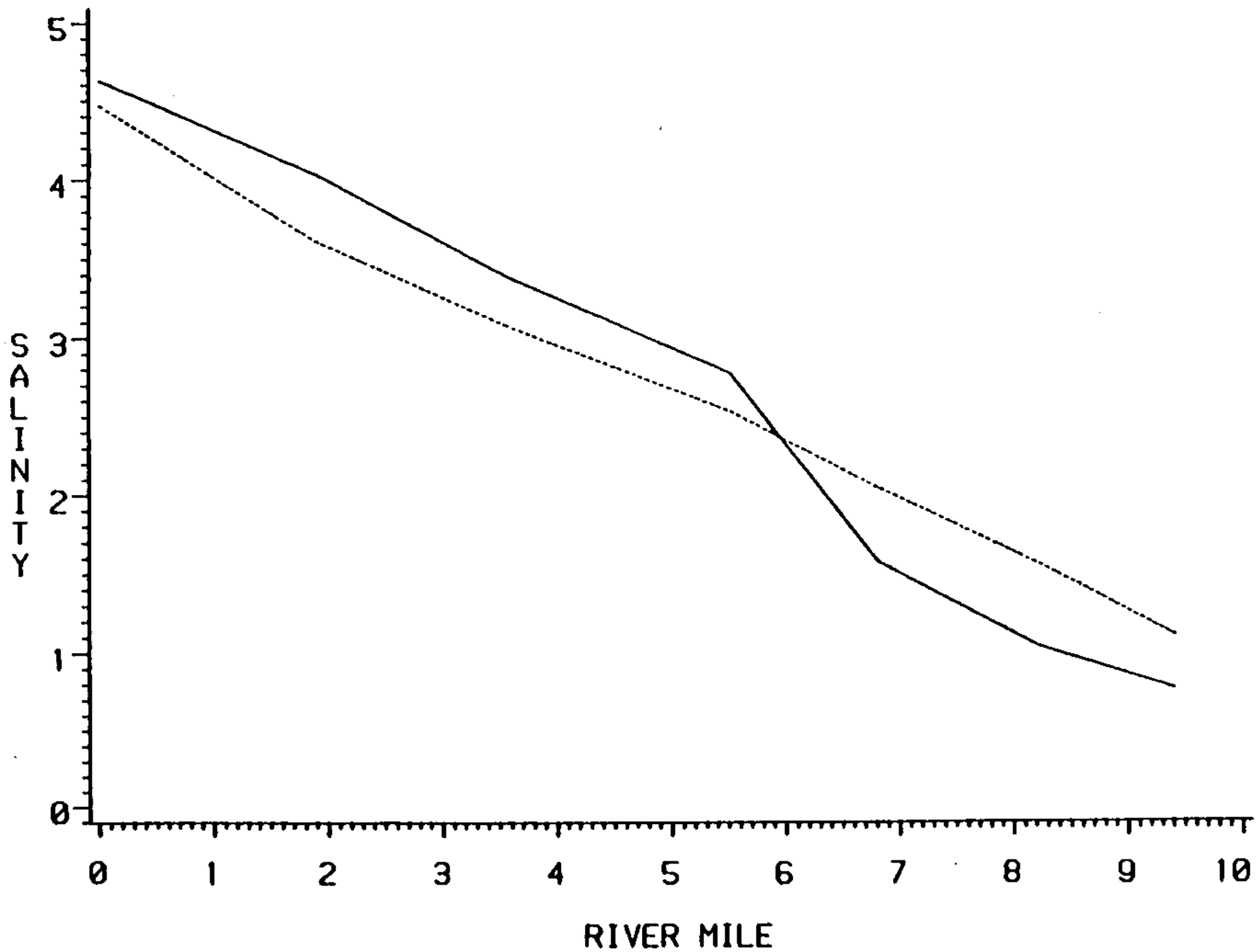

Figure II-10. Calibration of model dispersion. Observed salinities along Bush River (solid) vs. tidally-averaged salinities predicted by the model (dotted) by river mile for 2 October 1972

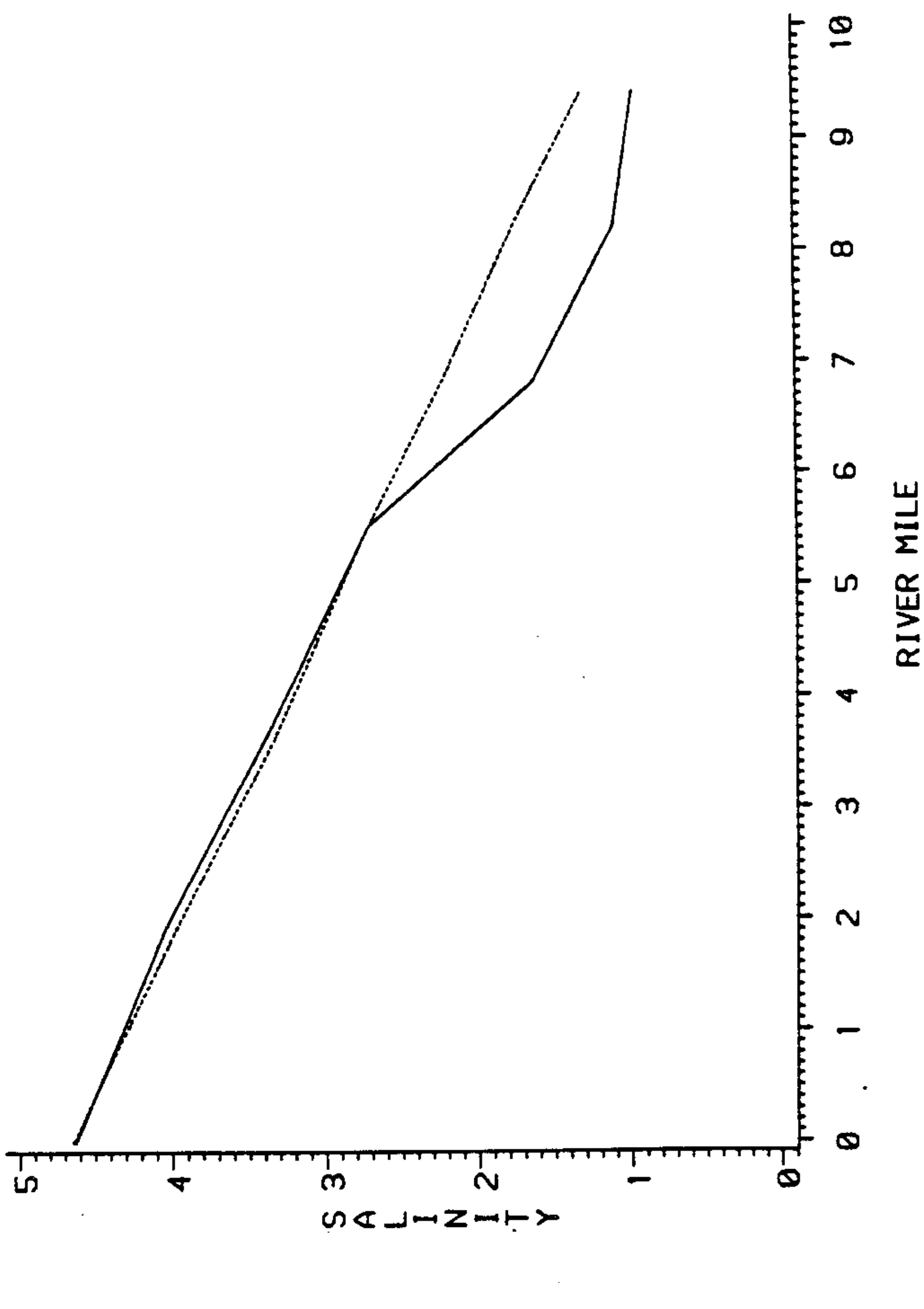

Figure II-11. Calibration of model dispersion. Observed salinities along Bush River (solid) vs. tidally-averaged salinities predicted by the model (dotted) by river mile for 3 October 1972

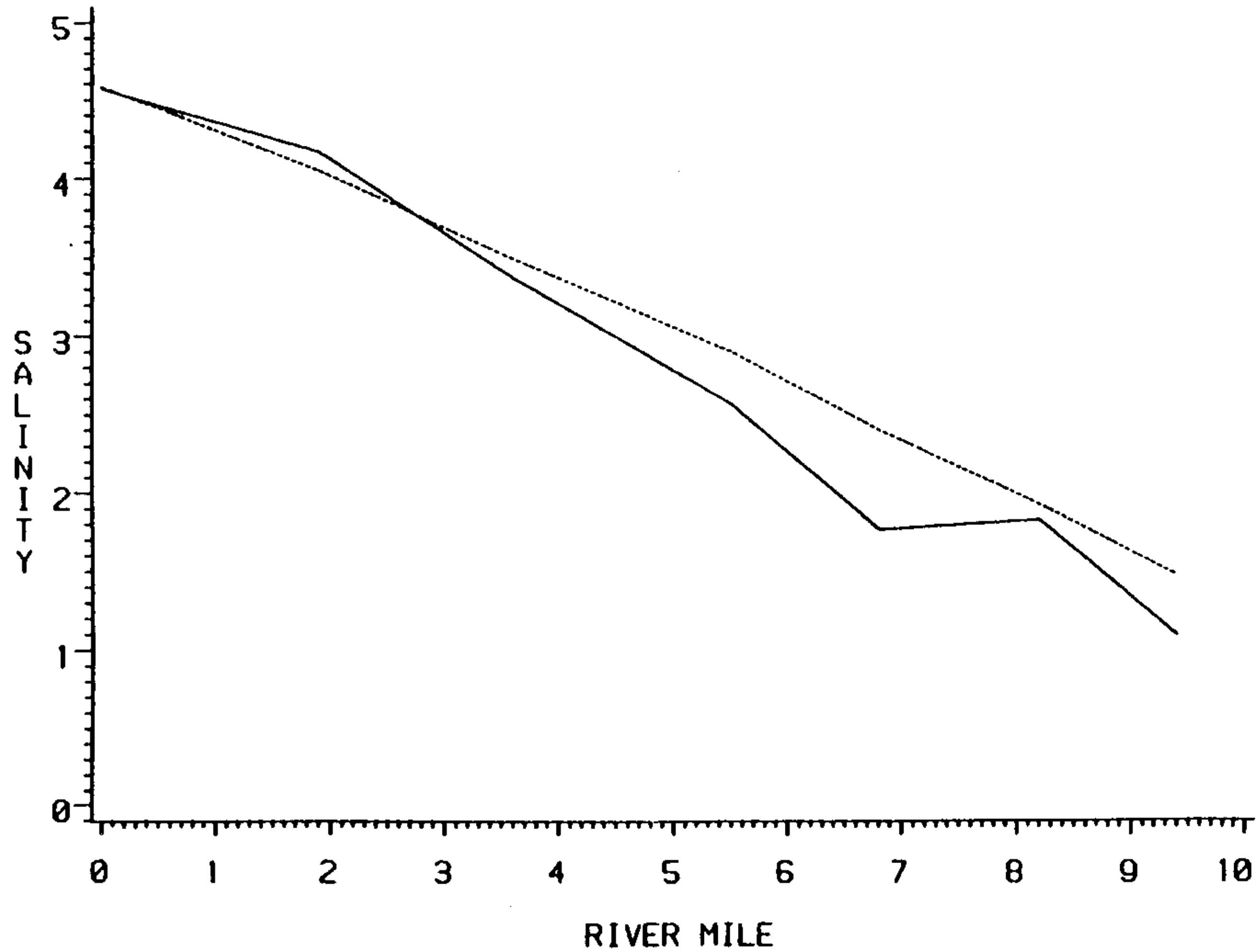

Figure II-12. Calibration of model dispersion. Observed salinities along Bush River (solid) vs. tidally-averaged salinities predicted by the model (dotted) by river mile for 4 October 1972

E. USE OF THE HYDRAULIC MODULE FOR SIMULATING ESTUARINE CIRCULATION DURING OTHER PERIODS

As described above, the Hydraulic Module of DEM has been calibrated and validated, and can now be used to simulate the hydrodynamics of the estuary for other periods of interest (e.g., time intervals needed to calibrate the Water Quality Module or to simulate hypothetical scenarios involving Perryman Power Plant discharges). In order to run the Hydraulic Module for other time intervals, initial and boundary conditions for the model network must be specified. This section describes the specification of those initial and boundary conditions.

Initial Conditions

The initial conditions selected for running all scenarios involved setting the heads (H) of all 12 junctions to a value of 0 at t = 0. In other words, the sea levels of all junctions were set to Mean Low Water.

Boundary Conditions

Tributary Inflows

To run the model, daily values of the three tributary inflows were specified based on USGS data for the gauge on Winter's Run (Station 01581700, near Benson, MD). Streamflow values for the three tributaries were derived from the ratio of the tributary's watershed area to that of Winter's Run above the gauge.

Once daily values for each tributary were specified, values for each time step were interpolated between the daily values.

Seaward Boundary

The specification of the seaward boundary condition for the model involved the estimation of tide data for the mouth of the estuary. With the exception of the tide data collected for use in calibrating the Hydraulic Module (23 September-11 October 1984), tide data were never collected at the mouth of the Bush River. Consequently, part of the Perryman study focused on identifying the best way to estimate the needed tide data using several sources of available information.

Three different methods were evaluated as means of estimating the needed tide data:

- A quantitative relationship between wind and sea level, which could be used to calculate sea level for any period for which wind data are available

- A relationship between the 1984 Bush River data and the data from the Havre de Grace tide station, based on a cross-spectral analysis of the two data sets; the cross-spectral relationship can be used to convert Havre de Grace tide data covering other periods into the needed Bush River data

- A simple ratio between the amplitudes of the 1984 Bush River tide data and data from a nearby NOAA station (Havre de Grace, MD), which can be applied to data from the NOAA station covering other periods.

These methods are described in detail in Appendix A. We decided to use the ratio method for the estimation of the seaward boundary condition for model runs involving conditions between 1972 and 1984 because it generally provided the best fit to data.